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A review on contemporary computational programs for Building's life-cycle energy consumption and greenhouse-gas emissions assessment: An empirical study in Australia

W.Y.Vivian Tam [a, b, *], K.N. Le [a], C.N.N. Tran [a], J.Y. Wang [b]

[a] School of Computing Engineering and Mathematics, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia
[b] College of Civil Engineering, Shenzhen University, Shenzhen, China

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ABSTRACT

Choosing an effective and efficient building design option for energy management as well as for reducing greenhouse-gas (GHG) emissions associated with a building life-cycle is always highly challenging to any designers in the battle to tackle global climate change issues. Researchers around the world are thriving in building optimization models for developing strategies that would result in an overall reduction of a building's energy consumption aside from decreasing GHG emissions.

Despite using similar input data sources, challenges to get similar results which are simulated from different software to assess environmental and financial aspects in a life-cycle of a system are still the dilemma to all sustainable development designers. Another difficulty, which happens in the progress of sustainable development in Australia, is that designers may have to follow a variety of green building rating tools to minimize environmental footprint and to increase the efficiency of buildings operation during their lifetime. Time will be consumed if design options are not appropriately and automatically calculated and assessed. In order to obtain building's life-cycle assessment (LCA) along with to achieve Green Star's certificate, choosing an appropriate program to calculate life-cycle energy consumption, life-cycle cost and life-cycle GHG emissions are a necessity to designers. This paper presents a comprehensive review of all considerable researches focus on the biologically inspired algorithms to different fields of sustainable building designs and their module modelling development in recent years (up to 2016). Major fields are reviewed in detail, including building envelope design, comprehensive optimization of several areas simultaneously as well as configuration and control of building energy consumption.

The outcomes of this study can assist researchers to choose which program is the best suitable for their study on sustainable assessment. In Australia, based on these design, practitioners can decide the optimum option for their project which can achieve their sustainability goals as well as can be granted the Green Star's certificate less sophisticated.

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1. Introduction

Building's life-cycle assessment (LCA) is a technique to evaluate the environmental impacts throughout this building's lifespan. Guidelines for achieving LCA result is provided by The International Organization for Standardization (ISO) via ISO 14,040 (2006); ISO 14,044 (2006). Life-cycle cost, life-cycle energy consumption and life-cycle GHG emissions assessments form three streams of life-cycle studies have been used to evaluate environmental impacts of building construction (Aïtcin and Mindess, 2011; Chau et al., 2015; Tam et al., 2017a, b). Fig. 1 shows the theoretical procedure of LCA, which evaluates all the resources inputs of a product including energy consumption, water and materials, and GHG emissions, solid and liquid wastes, at many stages such as production, construction, use and end of life stage of building. Whilst life-cycle energy analysis is an approach that accounts for all energy inputs to a building in its life cycle, GHG emissions are assessed as the construction output to the environment from cradle to grave of the building (Ramesh et al., 2010; Chau et al., 2015).

Developing building models for estimating life-cycle energy

* Corresponding author. School of Computing Engineering and Mathematics, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia.
E-mail address: vivianwytam@gmail.com (W.Y.Vivian Tam).

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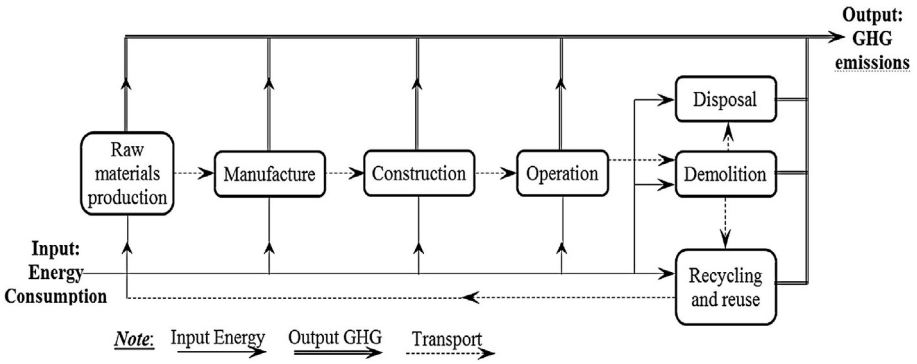

Fig. 1. Theoretical process of Life-cycle assessment (LCA).

consumption as well as life-cycle GHG emissions is one of many contemporary approaches to address the global climate change challenges. Nowadays, with the assistance of a series of computer programs, calculation of the energy used in the building is easier than ever. There are many studies regarding the development of building models in order to manage GHG emissions produced from energy use in building operations. However, results from life-cycle environmental and economic impacts assessment of the same project by different LCA applications is not always be similar and coherent (Herrmann and Moltesen, 2015). That means hard to decide which design scenario will be more suitable for the environment as well as the investor's financial plan. This situation also happens in the sustainable design community in Australia, the country has pledged a plan to decrease about 26% of GHG emissions by 2030 compared to 2005 GHG emissions level (Shahiduzzaman and Layton, 2015).

In the Australian context, Green Star rating tool is developed and supported by a non-profit organization and this tool covers many criteria and evaluates buildings as a whole in terms of environmental impact. These multi-objective elements are analogous to the requirements of Credit 15 in “Green Star (Design & As Built)”, which refers to GHG emissions reduction associated with energy usage in building operations which can demonstrate by employing “best practice” option of building fabric (Green Building Council of Australia, 2015a). The up-to-date literature has consolidated that the building envelope, glazing, lighting, and heating ventilation, and air conditioning (HVAC) could have a significant influence on the energy consumption during operation stage (Lawania and Biswas, 2016). This is also important to analyse energy supply sources during the life of building including coal, natural gas, oil and other resources which play the fundamental role of energy production (Aguirre-Villegas and Benson, 2017; Sági et al., 2017; Xia et al., 2017). In order to quantify these products' impacts on the environment and to use alternative products, there is neccessity of synthesizing multiple databases and assessing methodologies. This requires the use of software that integrates those methods and databases to improve the accuracy and computational efficiency of these energy sources analyses.

In addition to granting a Green Star certificate, the assessment of the impact of these factors along with energy consumption throughout the life of the project on the environment and economic decisions is also fundamental to all owners, practitioners and whom may be related to the project. As such, achieving a specific Green-Star credit for the industry seems challenging if the assessment process is not well-prepared and user-friendly.

Different algorithms predicting building energy consumption can be varied from modelling of a single component (a slab, a wall, etc.) to modelling of a whole building in different climate conditions (Harish & Kumar, 2016). These computational models can be used to support sustainable design analysis, which could be referred to as rapid and quantifiable feedback on diverse sustainable alternatives and ‘what if’ questions posed by a design team and client in the early planning stage (Emmitt, 2013).

For the purpose of Australian sustainable development approach in generally and Green-Star in particularly to estimate LCA of the buildings, construction projects should be assessed consistently with the requirements of the Building Energy Analysis Software protocol in Australian Building Code Board. The recently environmental analysis programs always have their own advantages and disadvantages in demonstrating every corner of the practical building to comply with the protocol's requirements. And choosing which software in the early and middle phase of project design to evaluate the energy efficiency as well as ecological impacts is also always a genuine question to designers and project planners. The aims of this paper are to (1) summarise global researchers in computational modellings for building's energy and GHG emissions conservation in the recent years; (2) compare their algorithms which have to automate life-cycle GHG emissions estimation process by simultaneously identifying optimal building designs, energy efficient appliances and optimal on-site renewable energy supply system designs affordable to the requirements in Credit 15 in Green Star (Design & As Built) and (3) recommend suitable software for life-cycle cost calculation as well as life-cycle GHG under Green Star criteria. The outcomes of this study can assist practitioners and designers have a fresh view on the development of suitable and sustainable software.

The structure of this paper is as follows. Section 2 contains an overview of international green building rating systems and summarizes the “Energy” criteria in Green Star rating tool which contains major points in this rating system; Section 3 discusses the technique classification on building energy simulation model; Section 4 provides views on flagship life-cycle assessment programs: GaBi and SimaPro; Section 5 discusses the application of these programs to achieve Green Star criteria requirements in Australia.

2. Common green building rating systems in the world

2.1. International green building rating systems

Several international green building rating systems consist of LCA that is presented in Table 1 (Al-Ghamdi and Bilec, 2016; Illankoon et al., 2017). There are 27 countries with established green building councils classified into five major regions around the world, which including: Leadership in Energy and Environmental Design (LEED) by United States Green Building Council, California

Table 1
Current green building rating tools around the global.

Region	Country	Name of the green building council (GBC)	Green building rating tool
Africa	South Africa	GBC South Africa	Green Star SA (adapted from Green Star Australia)
America	Argentina	Argentina GBC	LEED
	Brazil	GBC Brazil	LEED, AQUA (Alta Qualidade Ambiental)
	Canada	Canada GBC	LEED Canada, Green Globes
	Chile	Chile GBC	LEED
	Columbia	Columbia GBC	Selo Ambiental Colombiano para las Edificacionis (SACE), [Colombian Environmental Seal for Sustainable Building]
	Peru	Peru GBC	LEED
	USA	US GBC	LEED, Green Globes
Asia -Pacific	Australia	GBC Australia	Green Star
	Chinese Taipei	Taiwan GBC	EEWS (Ecology, Energy saving, Waste and Health), LEED
	New Zealand	New Zealand GBC	Green star adapted from Green Star Australia)
	Hong Kong	Hong Kong GBC	BEAM Plus (Building Environmental Assessment Method)
	India	Indian GBC	IGBC (Indian Green Building Council) Rating, LEED
	Japan	Japan Sustainable Building Consortium	CASBEE (Comprehensive Assessment System Built Environment Efficiency)
	Malaysia	Malaysia Green Building Confederation	Green Building Index
	Singapore	Singapore GBC	Green Mark
Europe	Croatia	Croatia GBC	LEED, BREEAM, DGNB (Deutsche Gesellschaft fur Nachchaltiges Bauen)
	France	France GBC	HQE (High Environmental Quality)
	Germany	German Sustainable Building Council	DGNB, BREEAM Germany
	Netherlands	Dutch GBC	BREEAM
	Poland	Polish GBC	LEED, BREEAM
	Spain	GBC Espana	VERDE (Green) (From SB Tool), BREEAM, LEED
	Sweden	Sweden GBC	BREEAM SE (Swedish version), LEED
	Turkey	Turkish GBC	BREEAM, LEED, DGNB
	UK	UK GBC	BREEAM
Middle East and North Africa	UAE	Emirates GBC	LEED, BREEAM, ESTIDAMA
	Jordan	Jordan GBC	LEED

Green Building Standards (CALGreen) by California Building Standards Commission, Building Research Establishment Environmental Assessment Methodology (BREEAM) by U.K.Building Research Establishment, Green Globes by Green Building Initiative, Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) by Japan Sustainable Building Consortium, Green Star by Green Building Council of Australia, Building Environmental Assessment Method (BEAM Plus) by Hong Kong Green Building Council, Green Mark by Building Construction Authority Singapore, and International Green Construction Code (IgCC) by International Code Council (ICC), etc.

In terms of green building rating tool utilization, BREEAM and LEED are widely represented in the American, European and North Africa as well as are used as a model to form other tools such as Green Star in Australia or HK-BEAM in Hong Kong (Ding, 2008; Alyami and Rezgui, 2012; Tam et al., 2017a, b). In accordance to the ISO 14,040 series, a “cradle to grave” assessment for building should be implemented to improve the building's environmentally friendly aspects (International Organization for Standardization, 2006). And one major phase in the building life is operation phase that can be assessed by 'Energy' criteria. That can be seen in Table 2, ‘Energy’ criteria has been found to have the highest weightings on all the green building rating tools with the exception of CASBEE (Villoria-Saez et al., 2016; Illankoon et al., 2017).

2.2. Australian context Green Star's rating tool

Total building energy consumption in Australia is projected to rise by 24% over the period 2009 to 2020, reaching expectedly under 170 Petajoule (PJ) by 2020, as reported in National Strategy on Energy Efficiency by Council of Australian Governments (COAG) (2012). Green Star Environmental Rating System is one of green building rating systems in Australia. The purpose of this green building rating tool is to support the construction industry in its evolution to sustainable and environmental-friendly development.

The ‘Energy’ criterion occupies 24 out of 100 points in the Green Star (Design & As Built). In these points, to encourage the reduction of GHG emissions associated with energy usage in building operations, up to 20 points can be achieved in Credit 15 alone. In the Credit, ‘Energy’ contains all energy types used in building's operation, including electricity, gas, oil or diesel according the National Greenhouse and Energy Reporting scheme (Green Building Council of Australia, 2015a). The Credit addresses five flexible substitute pathways in demonstrating GHG emissions reductions: (1) 15A Prescriptive Pathway; (2) 15B NatHERS; (3) 15C BASIX; (4) 15D NABERS; and (5) 15E Modelled Performance. In order for the project to be eligible for Green Star (Design & As Built) certification, a conditional requirement must be met for each of the five pathways, which is demonstrated by using a modelled performance approach or a prescriptive approach as outlined within each pathway described in the Credit. By referring to the Australian's National Construction Code (NCC), an applicable version is the edition referenced in the Building Surveyor's report for the project, or the version of the edition that is current at the date of the project's registration for Green Star certification (Green Building Council of Australia, 2015a).

The Credit 15A Prescriptive Pathway can be awarded up to a maximum of five points from eight building elements including building envelope (one point), glazing (one point), lighting (one point), ventilation and air-conditioning (one point), domestic hot

Table 2
Energy criteria weighting in international green building rating tools.

Tool	Energy criteria (%)	Maximum green building credit points
LEED	30.43	115
BREEAM	23.08	130
Green Star	24.00	100
Green Mark	49.73	183
GBI	39.36	94
BEAM plus	34.29	140
IGBC	29.17	96
CASBEE	8.43	83

water systems (one point), building sealing (one point), and Accredited Greenpower® (One to two points) of the building, which is classified in NCC's Classes 3 to 9 achieving Section J minimum requirements.

Up to 12 points are available in the Credit 15B NatHERS. This method only applies to Class 2 multi-unit residential dwellings located in all states and territories in Australia, except in New South Wales. The project must achieve a minimum NatHERS 0.5-Star rating improvement on the minimum legislated area-weighted average. This pathway divides into two categories: (1) thermal and energy performance; and (2) building services, sealing testing and appliances. The credit element of energy intensity reduction is awarded six points on the calculated energy reduction intensity in the base MJ/m^2 metric rather than the NatHERS star rating score. Nine points of specification and design checks for lighting, domestic hot water, building sealing and appliance efficiencies as well as ventilation systems are considered, however a maximum of six points may be awarded.

The Credit 15C BASIX also applies to Class 2 multi-unit residential dwellings but just only for projects located in New South Wales. The method can use for Class 1 dwellings, nevertheless the relevant clauses need to be adapted to the relevant BASIX compliance criteria applicable to these building types and their construction methods. GHG emissions reduction of the project through thermal performance improvement and efficient building services, appliances and equipment utilization can lead to up to sixteen points in this pathway. Points are calculated by using the Green Star Performance GHG Emissions.

The Credit 15D NABERS can also achieve sixteen points. In the Credit 15D, points are achieved on the estimated reduction in the NABERS baseline and interpolated using the Green Star (Design & As Built)'s GHG Emissions Calculator (Green Building Council of Australia, 2015a; 2015b).

The Credit 15E – Modelled Performance applies to Classes 2 to 9 buildings. In this pathway, the proposed building GHG emissions should be demonstrated less than those of the equivalent benchmark building. Up to 20 points can be achieved in this pathway, four out of these points can be granted from improving the building's fabric against a reference building and sixteen out of 20 points for reducing emissions against the benchmark building. A guide to the approximate points can be awarded in the Credit 15E is summarised in Table 3.

3. Techniques on building energy simulation model development

To analyse environmental impacts, researchers could use two major approaches, which are problem-oriented approach and damage-oriented approaches. In the problem-oriented approaches, the environmental involvements from some phases in life-cycle inventory (LCI) are analysed along with the ultimate damage caused by these involvements (Azapagic, 2006). Whereas, damage oriented approaches are commonly referred to as 'endpoint' methods due to they connect and model the environmental damage caused by the interferences to human habitats (Bare et al., 2000).

Several methods are classified follow the analysis of thermal transmission through building elements to develop building energy simulation models such as response factor methods, conduction transfer functions, finite difference methods, lumped capacitance models recently are preferred to combine to increase the strength of each method rather than using separately (Kramer et al., 2012; Harish & Kumar, 2014).

Room thermal response factors are a convenient way of using data on a room's dynamic thermal characteristics for air conditioning modelling, which was formerly introduced by Mitalas and Stephenson (1967). A time series of responses of room cooling load and surface temperatures is calculated from a time series of unit pulses by solving the heat balance equations for all the surfaces and the ambient air (Mitalas and Stephenson, 1967; Kramer et al., 2012).

The response of factors for a particular room's components, which contain the relevant information about the room including its size, construction type, colour, surface emissivity can be combined with the appropriate excitation to obtain the response in a specific case (Stephenson and Mitalas, 1967). Conduction transfer functions, such as Laplace transform method, state-space method, direct root finding method, frequency-domain regression method, are an efficient method to compute surface heat fluxes because they eliminate the need to know temperatures and fluxes within the surface (Stephenson and Mitalas, 1967, 1971).

Finite difference method is a well-established and conceptually simple method to solve heat transfer problems (Ozisik, 1994), which requires a point wise approximation to the governing equations (Lewis et al., 2004). In this method, a wall is divided into a finite number of control volumes for which the heat balance equation are solved (Kramer et al., 2012). However, the finite difference technique becomes difficult to use when an unusual geometries are encountered (Lewis et al., 2004).

A lumped capacitance model, also known as lumped system analysis (Incropera, 2011) can be used to solve transient heating and cooling problems by reducing a thermal system to a number of discrete "lumps" and assumes that the temperature difference inside each lump is negligible (Virag et al., 2011). The representation of electrical networks, which are resistances and capacitances, is used to model a building element. A capacitance represents the thermal capacitance of (a layer of) a wall (Kramer et al., 2012).

In term of parameter identification techniques, physical or white-box (sometimes called glass box) modelling (Brause, 2010), statistical or black-box modelling, and physical statistical or grey modelling are using to buildings' energy consumption (Mustafaraj et al., 2011; Amara et al., 2015). As shown in Fig. 2, while a detailed and structured amount of building internal information are required to use in a white box method, the fundamental aspects of the system are investigated without or with a limited relevant with the building.

In the building energy community, a vast diversity of building performance programs has been developed. A summary of up-to-date energy simulation tools is shown in Table 4. Energy efficiency designs including building envelope, building orientation, and natural ventilation leading to cut depending on energy-consuming mechanical systems in maintaining comfortable indoor temperatures inside the building (Zhu et al., 2013). Accessing energy consumption in a life time of a building involves not merely energy demanding in the operation phase but also relates to material production, construction, demolishment as well as recycling stages (Yuan and Jin, 2015). This leads to the situation that the more practical building the more complicated model which experts need to develop to access precisely the building's environmental impacts.

Beside of numerous tools and plugins for model development in demonstrating building energy simulation, a case study by Crawley et al. (2008) has presented features of twenty major applications which are commonly used for building energy simulation, including BLAST, BSim, DeST, DOE-2.1E, ECOTECT, EnerWin, Energy Express, Energy-10, EnergyPlus, eQUEST, ESP-r, IDA ICE, IES/VES, HAP, HEED, PowerDomus, SUNREL, Tas, TRACE and TRNSYS. Since then, hundreds of programs have been developed and contained many methods in estimating energy performance such as whole-building energy simulation, parametric and optimization, model

Table 3
A guide to the approximate points can be awarded in the Credit 15E – Modelled Performance.

Credit element	Reduction (%)	Points Awarded
Energy Consumption reduction (Intermediate Building relative to Reference Building)	5%	1.0
	10%	2.0
	15%	3.0
	20% (maximum rewarded)	4.0
GHG emissions reduction (Proposed building relative to Benchmark Building)	10%	1.6
	20%	2.5
	30%	2.5
	40%	2.5
	50%	2.5
	60%	2.5
	70%	2.5
	80%	2.5
	90%	2.5
	100% (maximum rewarded)	2.5

input calibration, energy conservation measures, building energy auditing, life-cycle analysis, and cost analysis (Fig. 3), which

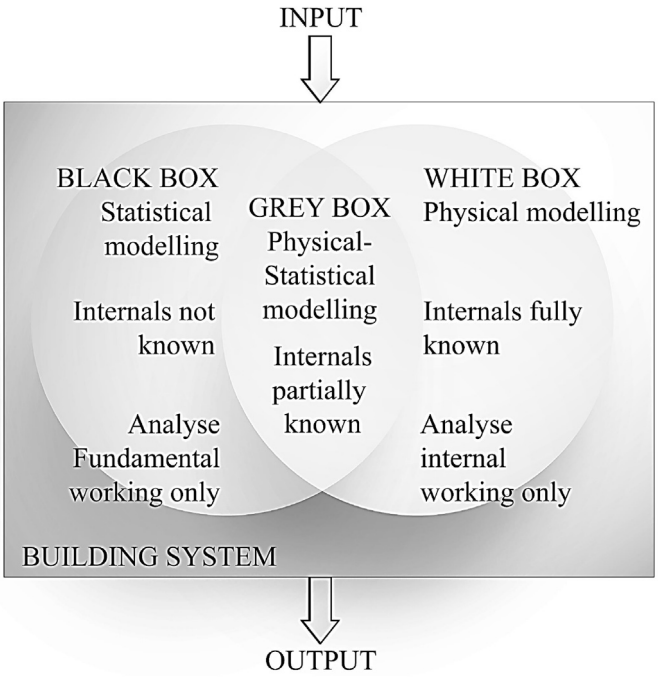

Fig. 2. Modelling classification in term of parameter identification techniques.

demonstrates the capabilities of 134 latest tools for building energy performance simulation (Hong et al., 2000; International Building Performance Simulation Association (IBPSA), 2017). However these high-end simulation engines, for instance DOE-2.2 and Energy Plus, expected tons of detailed information and time to simulate, which are always in short supply in the beginning phase of every project (Chowdhury et al., 2007).

In additional, the more structured tools tend to be simpler in design, whilst the modular/flexible simulation program requires additional modelling time (Michael Kilkelly, 2015). Since the first time introduction in 1970s, building energy management systems have become one of the trends that providing comfortable indoor environment and effectively utilising energy in buildings (Perera et al., 2016). Perera et al. (2016) used both Matlab and Modelica as the environments to cover multi-floor physics-based building heating models for the existing Norwegian three-storeyed residential building built in 1987. The Matlab model consists of 16 state variables including the air densities of each floor while the Modelica model illustrates the effect of wind, which is not included in the Matlab model. However, the model runs in Matlab environment is simpler, easier for any architectural configurations, and more comfortable to integrate into the building energy management systems after developing it using Object Oriented Language such as C# or Java than the Modelica.

While some investors' perspective is that buildings with low carbon development are harder to sell and less profitable is a barrier to commercializing housing which uses new technology to build a sustainable building, recent effective multi-objective optimization models will change these view and strengthen the investor's confidence in this green building direction (Hamdy et al., 2016; Khodabuccus and Lee, 2016). A baseline design was deployed by Khodabuccus and Lee (2016) using a detached four bedrooms property to acquire technical and economic linked model to optimise a zero carbon design and then develops a home using this technique. The model was run in TRNSYS application and was divided into 15 individual thermal zones with different occupancy patterns and usages. Standalone tools and plug-ins which contain whole-building energy simulation capability in the building's life-cycle along with flexible methods in geometrically creating accurate input files have currently been developed in order to easily integrate into existing building information modelling tool and enable for regular checking on building performance in the early planning stage (Michael Kilkelly, 2015).

In the LCA community, OpenLCA Nexus is a free software which is developed by GreenDelta GmbH to develop a footprint model with a huge library of free and purchased databases. However it requires developers have knowledge about SQL, Python or Java Script languages. Besides, with free database options, the program is still quite simple to build a complicated model such as a whole building model in a practical climate condition (GreenDelta GmbH, 2017). To facilitate practitioners in estimating energy consumption

Table 4
Up-to-date life-cycle assessment tools.

Program	Working environment	Output	Cost	Developer
IES	a1, a2, a3, a4	b1	Variable	IES
GaBi	a4	b1	Variable	Thinkstep
Sima Pro	a4	b1	Variable	PRé Sustainability
EnergyPlus	a2	b1, b2	Free	US DOE
Sefaira	a1, a2	b1	Variable	Sefaira
GBS	a1, a4	b1, b2, b3	Autodesk extension	Autodesk
OpenLCA Nexus	a4	b1	Free	GreenDelta GmbH

Note: a1: Autodesk Revit; a2: SketchUp; a3: Vectorworks; a4: Other modelling programs exports to Green Building XML schema (gbXML).
b1: whole-building energy simulation; b2: energy conservation measures; b3: GHG emissions reporting.

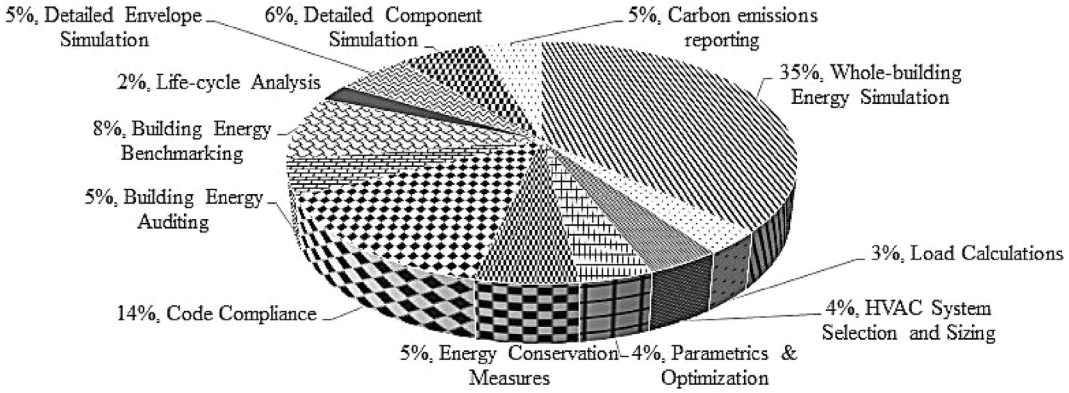

Fig. 3. Capabilities of building energy performance simulation tools.

for a building, National Laboratory of the U.S. Department of Energy (2017) develops OpenStudio® as an open source cross-platform that is used EnergyPlus and Sketchup to support whole building energy modelling. Although this software is freeware, its SketchUp plug-in is required run in the updated SketchUp Pro version which would be purchased via the Trimble Inc. (2017)'s website, for example the latest version 2.2.0 of OpenStudio® is only supported in Sketchup Pro (2017). Or even, experts can utilise Microsoft Excel to develop their own model. However, to build such kind of model, they need to put a great effort to develop their own database as well as analyse big data from input and output resources which require executing by other plug-ins such as Visual Basic or other programming languages that match with Microsoft Excel (Vivian WY Tam, 2017). One part of the project implemented by the paper's authors has been developed in Microsoft Excel and Visual Basic. The results of this study will be presented in another paper.

4. Discussion

Although there are a variety of tools for developing building energy simulation models, researchers worldwide prefer to use two leading and mostly-commonly used LCA programs, GaBi and SimaPro for estimating the use of energy in building operations rather than other programs due to their outstandingly massive life-cycle database as well as their flexibility in design many types of environmentally friendly products and systems (Herrmann and Moltesen, 2015; Židonienė and Kruopienė, 2015; Sinha et al., 2016; GaBi, 2017b; SimaPro, 2017b). Recent works used these programs to assess life-cycle GHG emissions as well as life-cycle energy consumption are summarised in Table 5. A standard LCA established by International Organization of Standardization (ISO) in The International Organization for Standardization (ISO) (2006b, 2006a) which includes goal and scope, LCI, life-cycle impact assessment and interpretation (Al-Ghamdi and Bilec, 2016) is available.

These two LCA tools cover within the boundary of the building life-cycle (Linfei et al., 2011; Zhang and Wang, 2015), mainly during the following processes which cover the energy used across all stages of the lifespan of the building, including: material production, maintenance and substitution, and eventual phase of lifecycle (which includes disposal and/or recycling phases) (Al-Ghamdi and Bilec, 2016; Vivian WY Tam, 2016). Both applications can analyse material using scenarios or building envelop options of a genuine building to simulate its energy consumption as well as to generate air emissions during its lifetime (Islam et al., 2010; Broun and Menzies, 2011; Ximenes and Grant, 2013; Bueno et al., 2016; Islam et al., 2016; Kua and Lu, 2016; Sim et al., 2016). The analysis on external wall structure systems in the context of Brazilian buildings was conducted by Bueno et al. (2016) using GaBi and the Ecoinvent database 2.01. This LCA study compared the results of assessment of four structure types: masonry of clay blocks, masonry of concrete blocks, concrete wall and cement panels with steel framing system by five different life-cycle impact assessment approaches. Beyond these approaches, Impact World+ method which is the most updated initiative is evaluated as the most appropriate methodology. However, this study also indicates there are still lacks of practical LCA tools justify most environmental data around the world. Kua and Lu (2016) contribute an environmental assessment of windows which use tempered glass and polycarbonate. In this model, data for all procedures in the production phase were multiplied with the databases in Ecoinvent, GaBi (2017a) and Inventory of Energy and Carbon (ICE) (Hammond and Jones, 2008) by a factor of the impact caused by 1 MJ of the Singaporean and Malaysian energy mixes to that of the European mix. The case study of a 25-storey building's lifetime in South Korea which has been assessed by Sim et al. (2016) also by GaBi. Following the analysis, concrete and steel contribute major environmental impacts with regard to global warming potential, acidification potential, and eutrophication potential, while the cement and the glass is the major source of the ozone depletion potential. SimaPro is also used to develop several models to assess GHG emissions as well as energy consumption. Lawania and Biswas (2016) recommends the optimum option among 60 envelope options for a typical house in Perth, Australia comprising using an LCA approach by using SimaPro with the AusLCI database (Australian Life Cycle Assessment Society (ALCAS), 2017).

Regarding to the case of existing building, researchers can study the optimum renovating option which has least environmental impacts (Techato et al., 2009; Iyer-Raniga and Wong, 2012; Mangan and Oral, 2015). The approach that mentioned in Fig. 1, which can be used to assess automatically the life-cycle impact of a building via the energy consumption (input data) in each phase as well as the GHG emissions (output data) of these stages, can be applied in GaBi and SimaPro (Desideri et al., 2014; Weiβenberger et al., 2014). Mangan and Oral (2015) used GaBi and ICE to access life-cycle energy and life-cycle carbon emission for the renovation options regarding to improve the existing residential building's energy performance in Turkey. The net-zero emissions building performance in Norwegian context was investigated for energy consumption in operation phase and embodied emissions in material by SimaPro with the Ecoinvent version 2.2 (Georges et al., 2015). According to the study, the electricity supply on the performance of these net-zero emissions buildings is strictly tighten with the scenarios for GHG emissions and embodied energy in materials and

Table 5
Review of case studies use GaBi and SimaPro for developing models to access life-cycle GHG emissions and energy consumption (2009–2016).

Author (Year)	Variable	Program	Building type	Objective	
Sim et al. (2016)	Materials properties	GaBi	Residential	i	
Kua and Lu (2016)	Materials properties	GaBi	Residential	i	
Bueno et al. (2016)	Materials properties	GaBi	Multipurpose	i	
Lawania and Biswas (2016)	Building envelope	SimaPro	Residential	i	ii
De Souza et al. (2016)	Building envelope	SimaPro	Multipurpose		ii
Islam et al. (2016)	Building envelope	SimaPro	Multipurpose		ii
Wang et al. (2015)	Energy consumption	SimaPro	Residential	i	ii
Mangan and Oral (2015)	Energy consumption	GaBi	Retrofit	i	ii
Georges et al. (2015)	Building envelope	SimaPro	Residential	i	
Islam et al. (2015a, b)	Building envelope	SimaPro	Residential	i	ii
Weißenberger et al. (2014)	Energy consumption	GaBi	Zero energy buildings	i	ii
Desideri et al. (2014)	Energy consumption	SimaPro	Multipurpose	i	ii
Condeixa et al. (2014)	Building envelope	GaBi	Residential	i	
Asdrubali et al. (2013)	Energy consumption	SimaPro	Multipurpose	i	ii
Ximenes and Grant (2013)	Materials properties	SimaPro	Residential	i	
Basbagill et al. (2013)	Materials properties	SimaPro	Multipurpose	i	
Kulahcioglu et al. (2012)	Materials properties & Energy consumption	GaBi	Multipurpose	i	ii
Iyer-Raniga and Wong (2012)	Energy consumption	SimaPro	Retrofit	i	
Gaidajis and Angelakoglou (2011)	Energy consumption	GaBi	Office		ii
Broun and Menzies (2011)	Materials properties	SimaPro	Multipurpose		ii
Blom et al. (2011)	Energy consumption	SimaPro	Residential	i	ii
Islam et al. (2010)	Materials properties	SimaPro, Accurate	Residential	i	ii
Ortiz-Rodríguez et al. (2010)	Materials properties	GaBi	Residential	i	ii
Dawood et al. (2009)	Building envelope	SimaPro	Multipurpose	i	ii
Techato et al. (2009)	Energy consumption	GaBi	Retrofit	i	ii

Note: (i): life-cycle GHG emissions; (ii): life-cycle energy consumption.

construction. GaBi and SimaPro are not the dedicated architecture design software but rather than a whole-life-cycle estimation program with an enormous material database inventories for over 60 countries, including Australian LCI library (Architecture and Design, 2016; GaBi, 2017b; International Building Performance Simulation Association (IBPSA), 2017; SimaPro, 2017b). Material quantities, which must be supplied in the LCIs development, could be estimated in both two programs. The characterization of the building materials, building constructions, space types, which would be analysed to achieve the credit points in Green Star can be both used from their databases as well as added from external sources in these tools (Green Building Council of Australia (2015a); Autodesk Sustainabiltiy Workshop, 2017; International Building Performance Simulation Association (IBPSA), 2017). Sustainable development creates an efficient and economical approach to build cleaner and greener buildings for society. Both GaBi and SimaPro have their individual and unique databases and methods to assess energy consumption as well as GHG emissions released during the building's lifetime. As claimed in the introduction, the paper will determine whether theses programs are suitable to use LCA approach along with the Green Star appliance. The following are the findings of this study.

4.1. The compatibility of GaBi and SimaPro with Green Star rating tool

In Australia, Green Building Council of Australia encourages the GHG emissions reduction along with the energy consumption during the building operation via five alternative pathways. The pathways in Green Star's energy credit are demonstration that the proposed building successfully complies the requirements in NatHERS rating tool by Nationwide House Energy Rating Scheme (2007) for dwellings located in all states and territories in Australia, except New South Wales (Credit 15B), or in BASIX assessment tool by NSW Government, The Building Sustainability Index (2009) for projects located in New South Wales (Credit 15C), or in NABERS Energy Commitment Agreement by National Australian Built Environment Rating System (2013) (Credit 15D). The other pathways also require the predicted building demonstrate its GHG emissions have been reduced by employing 'best practice' elements in Credit 15A or less than those in the reference building in Credit 15E (Green Building Council of Australia, 2015a).

According to Renouf et al. (2015), Myhre et al. (2013), the optimum practice recommendation for LCA in Australia is the Centre for Environmental Studies (CML) method which is developed by the Institute of Environmental Sciences, Leiden University, Netherlands (Guinée, 2002), as this aligns best with the Australian Environmental Product Declaration scheme's requirements. Both GaBi and SimaPro can be applied the normalization step of CML 2001 method. However, despite applying the similar methodology, results from these applications are still notably different due to their different normalization reference approaches of this method, for example, the significant higher factor of carbon footprint for emissions of hydrogen fluoride to air in GaBi or different assigned name of chromium emissions in each software (Herrmann and Moltesen, 2015).

To achieve up to 20 points in Green Star, practitioners can use both these programs to assess energy consumption and GHG emissions associated with the construction (Green Building Council of Australia, 2015a; 2015b). Because both applications allows substantial emphasis of the role of LCA in product development and provides increased sensitivity for environmental (Techato et al., 2009), the processes also can be customized the project's desired parameters in the analysis (Salcido et al., 2016). The results accuracy depends on the data available in the software database (Weiβenberger et al., 2014; Židonienė and Kruopienė, 2015).

As can be seen in Fig. 4, to achieve credit points from those pathways, both GaBi and SimaPro provide options to calculate and assess not merely the building's energy consumption but also the impacts of by their ability in providing a significantly efficient estimation engine in accompany with the update impact assessment approaches and the vast updated database of energy-related elements (building fabric, glazing, air conditioning & ventilation systems, heat water supply, etc.) which are mentioned in NCC (Australian Building Codes Board (ABCB), 2013).

Table 6 shows that whether the parameters input of the model

Fig. 4. Possible implications of GaBi and SimaPro along with Credit 15 in Green Star, Australia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

acknowledge or not (which means practitioners should choose white, grey or black box approach), both these LCA programs still satisfy the model's requirements with the flexible integration with a number of eco-databases, i.e. Ecoinvent, U.S.LCI, AusLCI database, which provides well documented process data for thousands of products, assisting experts make truly informed options about their eco-friendly impact. With these software's huge library of environmental impact analysis methodologies, it is possible for any expert idea that used available methods today within the LCA framework such as ReCiPe 46, International Reference Life Cycle Data System (ILCD) by GaBi and SimaPro (Finnveden et al., 2009; European Commission, 2010; National Renewable Energy Laboratory, 2012; Islam et al., 2015; Milieu, 2016; Adibi et al., 2017; Australian Life Cycle Assessment Society (ALCAS), 2017; Ecoinvent, 2017; GaBi, 2017a; SimaPro, 2017a). In term of products with multiple suppliers, GaBi seems to be a better option than SimaPro due to the reason that GaBi is able to construct a model with a range of different suppliers from its LCI datasets whilst it is not possible for SimaPro. Another considerable aspect is connection between different products, which is currently unachievable in SimaPro because its automatic creation of product system (Rodríguez and Ciroth, 2016). Some features in GaBi help this program giving better-optimized results than in SimaPro, which would change planner's decision in the earlier phase, such as higher aquatic eutrophication and lower global warming impact (Herrmann and Moltesen, 2015). However, Herrmann and Moltesen (2015) adjudicate that different results would be given with distinctive models developed by these platforms.

4.2. Challenges in using GaBi and SimaPro

Although both programs have huge databases of processes, flows and others aspects that related to forming a building model, these large databases themselves also make designers hesitant when choosing appropriate components for their model. Researchers have to go through this difficult in both cases. And this information refers mostly to generic procedures in Europe mainly due to the reason that both programs were first supplied in the European region, GaBi in Germany and SimaPro in Netherlands. Even their updated versions have repeatedly revised but they still have not fully covered the aspects of sustainable research in particular countries. For example, in GaBi, there are about 300 default processes for Australia. While in European region, it

Table 6
Features comparison between SimaPro and GaBi.

Features		SimaPro	GaBi
LCI database	Eco-Invent	☒ (Ecoinvent, 2017; SimaPro, 2017b)	☒ (Ecoinvent, 2017; GaBi, 2017b)
	U.S.LCI	☒ (National Renewable Energy Laboratory, 2012; SimaPro, 2017b)	☒ (National Renewable Energy Laboratory, 2012; GaBi, 2017b)
	AusLCI	☒ (Life Cycle Strategies, 2017; SimaPro, 2017b)	User need to contact thinkstep (Australian Life Cycle Assessment Society (ALCAS), 2017; GaBi, 2017b)
Modelling	Products without provider	☐	☒
	Modelloops	☒	☒
	Connections between different products	☐	☒
Ecological impact analysis methods	Midpoint approach methodologies		
	CML 37	☒	☒
	EDIP 2003 39	☒	☒
	TRACI 40	☒	☒
	Endpoint approach methodologies		
	Eco Indicator 99 41	☒	☒
	EPS 2000 43	☒	☒
	Eco Scarcity method (Eco points) 44	☒	☒
	JEPIX 45	☒	☒
	Combined midpoint and endpoint approach		
	RECIPE 46	☒	☒
	ILCD	☒	☒
	Impact 2002 + 49	☒	☒
	LIME 47	☒	☒
	LUCAS 51	☒	☒

Note: ☒: Feature enabled in the platform.

Table 7
A comparison of SimaPro and GaBi price in 2017.

License	GaBi	SimaPro
Perpetual license	~ USD 4000	Eur. 9500 ~ USD 11,000
Annual subscription	~ USD 1000 (need quote for other professional database packages)	Eur. 5000 ~ USD 5800

provides more than 600 processes.

Another limitation of creating a new building model to simulate energy and to calculate GHG emissions in these two programs is geographic demonstration, which would need to be applied for the model. In the process of design, practitioners still have to combine these LCA programs with the other design software such as Auto-Cad or Revit, etc. The application of whole-building LCA is complicate due to the variety of locations that model will be taken which will lead to the difficult of meteorological conditions data of these places. In addition, LCA results which are exported from these programs should be interpreted carefully by LCA experts and other practitioners to prevent any bias would be happened (Herrmann and Moltesen, 2015). This is a barrier for designers and other stakeholders who are not familiar with these programs would cope with.

These two programs have trial versions but functions for these types are limited and inadequate to build complicated models. These trial packages for education purposes have few databases just to allow users understand how these programs work. For commercial version, SimaPro seems to be more expensive than GaBi for both annual subscription and perpetual license as shown in Table 7. However, GaBi divides LCI databases into many packages that need to purchase to use for specific area of LCA.

5. Conclusion

Environmental change for sustainable development requires immediate action plans. Designing a “green” model to simulate a life-cycle of a building will be one of the effective paths of this progress. In order to improve productive an energy simulation model for a complex commercial building, LCA should be investigated with comfortable and interactive programs after or in the process of construction design. The combination of design is followed the requirements stated in “green” standards, for example point achievement of Green Star (Design & As Built) in Australia, and the building's LCA including life-cycle GHG emissions, life-cycle energy consumption, and life-cycle cost.

The goal of the paper is to assess appropriate software for a building's LCA along with achieving Green Star's requirements in reducing GHG emissions during the lifetime of a building. The review shows that there are varieties of programs that can estimate life-cycle energy consumption and/or life-cycle GHG emissions. As analysis in the paper, GaBi and SimaPro are two significant programs which are able to adapt the building model to several countries' green building requirements. LCI databases and environmental analysis methodologies provided in the programs are flexible that enable designers choose the optimum ecological option for their project. However, in order to access the professional license of both applications, planners need to put another miscellaneous item in their project's budget.

The key findings of the paper can be summarised as: (1) There are two notably well-known LCA software tools, GaBi and SimaPro, could be obtained sustainable requirements during the building's life. Both of these programs are widely used by sustainable projects' practitioners and other stakeholders. Both GaBi and SimaPro can be used to develop a model to assess life-cycle energy consumption and life-cycle GHG emissions of a building; (2) These software can be used with another computer-aided design programs to create a better whole-building model with geographical demonstration; (3) With a vast continuously updated LCA databases provided in both software for many countries and regions, GaBi and SimaPro meet the requirements of input-output approach methodology suggested in Green-Star. From thereon, designers can develop easily their drawing to achieve the requirements in this green building rating tool in Australia.

Nevertheless, based on the scientific level of research or the required perspective of the investors in green building design, choosing suitable programs to proceed an energy simulation model is always a crucial decision for any sustainable developers. In future, researchers should conduct additional samples for both programs in identifying the differences as well as errors, which would be reckoned. By then, the models would be closer to reality and help planners have accurate decision making for their sustainable projects. Based on these findings, we are planning to further expand this study to develop a model that is able to access the environmental impacts produced during the life-cycle of a building in the Australian context.

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